

Quantized Detector Networks: a Quantum Informational Approach to the Description and Interpretation of Quantum Physics

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February 1, 2008

Abstract

We discuss the QDN (quantized detector network) approach to the formulation and interpretation of quantum mechanics. This approach gives us a system-free approach to quantum physics. By this, we mean having a proper emphasis on those aspects of physics which are observable and an avoidance of metaphysical concepts, which by definition are incapable of verification and should play no role in science on that account. By focusing on only what experimentalists deal with, i.e., quantum information, we avoid the ambiguities and confusion generated by the undue objectification of what are complex quantum processes.

1 Introduction

The conceptual problems which arise in the interpretation of quantum mechanics have a common origin, which is the undue objectification of complex processes, such as those involved in observation. For example, when experimentalists say they have detected a particle, what they really should say is that they have done certain things which have had certain observed consequences. When theorists talk about a cat in a box, they conveniently ignore the vast number of degrees of freedom needed to define and maintain the biological state of the cat and talk about it as if it were a particle with two possible spin states. The fact is, it is possible to have a cat, parts of which are alive and parts of which are dead in a classical sense. It is, however, meaningless to talk about a quantum superposition of a living cat state with a dead cat state without any reference to the observational meaning of this superposition.

This tendency to use the language of objectification is a very natural one and frequently leads to meaningless debate about concepts incapable of verification,

such as how many angels can dance on the point of a pin [1]. Such language is used at all levels in science. Unfortunately, it is often based on the wrong mode of thinking where quantum mechanics is involved, because quantum mechanics deals with physics, not metaphysics. By definition, a metaphysical concept is one which implies a belief about the world around us, or about the wider universe, which may or may not seem entirely reasonable but is ultimately not provable or has no possibility of empirical validation.

We assert that quantum mechanics should be and can be discussed in a coherent, non-metaphysical way which bypasses the issue of system objectification. In this paper, we discuss an interpretation and formulation of quantum mechanics referred to as the QDN (quantized detector network) approach [2, 3]. This approach is based on treating the quantum information available to an observer as a primary concept, rather than on the concepts normally associated with SQM (standard quantum mechanics), such as Hamiltonians, observables, and states of systems under observation. The QDN approach may appear extreme from the SQM point of view but the benefits are immediate; we are no longer constrained to discuss the metaphysical concept of a system in isolation.

The mathematics of QDN is based on collections of quantum bits forming networks, the complexity of which is determined by the apparatus involved. These qubits represent the detectors of quantum information necessarily associated with any experiment. The result is an approach to quantum mechanics which not only gives a more faithful description of what actually happens in the laboratory compared to that given by SQM, but points to new ways of thinking about and describing physics.

Classical counterfactuality is the notion that properties of objects exist even if we do not measure those properties. The logic behind this idea is that if we had decided to measure a property of a system (which in fact we did not do), then we would have found that property, because it was there all along. Therefore we do not need to have measured it to justify our belief in its existence. This principle works wherever classical physics is valid.

Quantum mechanics, however, teaches us that classical counterfactuality is wrong in principle. The true laws of physics should be based on the quantum version of classical counterfactuality, which we shall call quantum counterfactuality. This is the idea that properties of objects do not exist independently of the context of observation. This was something Bohr understood but Einstein never accepted. The EPR thought experiment [4] was a powerful attempt by Einstein to undermine quantum mechanics by the subtle use of classical counterfactuality, and was only countered by Bohr [5] using the principles of quantum counterfactuality.

Quantum counterfactuality holds regardless of the temporal context of a statement. It holds whether we are discussing a situation involving the past, the present, or the future. It is an incredibly difficult principle to adhere to in discussions about physics, given our ingrained propensity to believe in classical counterfactuality. Even our statement of it here uses conventional language set in classical terms, but this does not detract from the validity of this principle.

By construction, QDN is based on quantum counterfactuality. QDN should

be able to describe not only everything that the PVM (projection-valued measure) and POVM (positive operator-valued measure) approaches in SQM can discuss in more systematic and efficient terms, but also readily deal with more complex scenarios such as time dependent apparatus, which SQM does not deal with efficiently. Here, we do not mean simply having a time dependent potential. We mean for example experiments which change their detecting apparatus whilst a given run is still in progress.

QDN is an attempt to discuss observation as a dynamical process involving observers and not as a passive process involving dynamical systems. It is related to quantum field theory, in that spatial degrees of freedom are implied in the formalism. In the limit where very many degrees of freedom are involved in an experiment, a quantum field version of the formalism should emerge[6]. QDN is also related to S-matrix theory [7], in that it can be viewed in terms of temporal sequences of scattering processes. It also bears some relationship to Schwinger's source theory approach [8], which is based on a local view of scattering processes. It is also related to consistent histories theories [9], with the fundamental difference that the histories involved are those of the apparatus, not of the system under observation and are always consistent on that account. This aspect of the QDN approach is discussed in our section of path integrals. Finally, QDN is allied to the formalism and thinking of quantum information and computation. From the QDN point of view, any quantum process can be described as a quantum computation.

2 The Stern-Gerlach experiment

In order to explain our approach, we start with a brief discussion of the SG (Stern-Gerlach) experiment [10]. In this experiment, a beam of charged particles is passed through an inhomogeneous magnetic field. If the particles are net carriers of a single electron, then it is observed that a beam of many such particles splits into two pieces, known as the *up* beam and the *down* beam respectively. The SQM description of this phenomenon is due to Pauli [11] and is based on the fundamental representation of $SU(2)$, the universal covering group for rotations in three dimensional physical space. In the two-dimensional Hilbert space \mathcal{H}^2 concerned, an orthonormal basis is chosen, consisting of one element $|+\mathbf{k}\rangle$ representing the *up* beam particles and another element $|-\mathbf{k}\rangle$ representing the *down* beam particles, where \mathbf{k} is a unit three-vector representing the spatial direction of the main magnetic field in the apparatus.

The point about using the Hilbert space representation in quantum mechanics is that vectors can be added. In the absence of any superselection rule, it is a general rule in quantum mechanics that we can prepare an initial state of the system (which in this case is usually thought of as a single electron) represented by the vector

$$|\Psi\rangle = \alpha|+\mathbf{k}\rangle + \beta|-\mathbf{k}\rangle, \quad (1)$$

where α and β are complex and satisfy the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. These squared moduli give the probabilities of each outcome, according to

the Born interpretation of SQM [12].

A number of questions arise at this point. First, there is the issue of locality. The SG experiment relies on the fact that the up and down beams intercept the detecting plate at different spatial locations. No account is taken of this in the superposition (1). Therefore, even at this very basic level, the formalism of SQM exhibits a form of non-locality.

Given this, it is difficult to interpret the superposition (1) as anything more than a metaphor for the experimental procedure. The expansion (1) has a significance, in that the vectors on the right-hand side correspond one-to-one with the possible detector sites. This would not remain true if we now introduced a different orthonormal basis in \mathcal{H}^2 , $\{|+\mathbf{a}\rangle, |-\mathbf{a}\rangle\}$, such that $|+\mathbf{k}\rangle = \frac{1}{\sqrt{2}}\{|+\mathbf{a}\rangle + |-\mathbf{a}\rangle\}$, $|-\mathbf{k}\rangle = \frac{1}{\sqrt{2}}\{|+\mathbf{a}\rangle - |-\mathbf{a}\rangle\}$ and rewrote (1) in the mathematically equivalent form $|\Psi\rangle = \frac{1}{\sqrt{2}}(\alpha + \beta)|+\mathbf{a}\rangle + \frac{1}{\sqrt{2}}(\alpha - \beta)|-\mathbf{a}\rangle$, *unless* we simultaneously rotated the apparatus so that its main magnetic field direction now pointed along direction \mathbf{a} , so that $|+\mathbf{a}\rangle$ now represented the new *up* beam states and $|-\mathbf{a}\rangle$ represented the new *down* beam states.

From such considerations, we feel entitled to infer that the vector additivity property of Hilbert space has no operational significance unless reference is made to the apparatus whose outcomes correspond to the terms in the summation. In other words, the context of observation (in this case, the direction of the main magnetic field) is a crucial factor which cannot be avoided in the quantum formalism. This is in line with the thinking of Bohr in his famous debate with Einstein on the interpretation of quantum mechanics [13]. When this point is neglected, it leads to conceptual issues such as the preferred basis problem in the relative state/Many Worlds interpretation of quantum mechanics [14] and theories of quantum decoherence [15].

We now come to the main thrust of our approach. At least *three* questions should be asked in any given run of the SG experiment. First, we must ask the question "has an electron been fired from the source or not?". In SQM, it is assumed that the answer is already *yes*, but in reality, a proper description of an experiment should involve such a question. We shall call this question, and its associated qubit, the *preparation switch*. It is a critical feature of the QDN approach, possibly the most important one, that every qubit in the network has the potential to act as a preparation switch for some subsequent process.

Next, consider the two potential detector sites, the *up* and *down* spots on the SG apparatus detector plate, *just before* a single electron is detected. At this time, the observer knows that each site registers nothing. Subsequently, given that an electron has gone through and registered somewhere in the apparatus (but we are not given where), the observer would ask the same question at each site, viz., "is there an electron here or not"? Therefore, contrary to the usual way of describing the SG experiment as a single question with two possible answers (i.e., spin *up* or spin *down*), the actual experiment poses *three* questions, each of which has two possible answers.

The essence of the QDN description of the SG and all other experiments is to assign a qubit to each place or situation where physicists could in principle detect

new information. These places need not be identifiable with distinct positions in physical space, but this is often the case. For instance, the detection of momentum information requires detection apparatus which is distributed over space in a carefully controlled way, such as in particle scattering experiments.

The qubits involved in the QDN description are related to each other via classical information held by the observer, and taken together, this forms the detector network referred to in our title. The quantum aspect refers to the time-dependent state of the network, which is represented by a vector, which we call the *labstate*, in the quantum register formed by the tensor product of all relevant network qubits. The labstate may be used by the observer to calculate the Born probability of any possible outcome, conditional on the answer to the preparation switch question being *yes*, prior to any detection. This probability gives the relative frequencies of the various possible outcomes, if sufficient runs of the basic experiment are performed.

For the SG experiment, the minimal QDN register is of rank three, i.e., involves the tensor product of three qubits, and is therefore a Hilbert space of dimension eight. This is markedly greater than the two dimensions used in the SQM Hilbert space description and is the price we have to pay for having a more complete description of what is going on. To deflect undue criticism on account of the higher dimensionality, we observe that a full quantum field theoretic description of even the simplest experiment would involve an infinite number of degrees of freedom, so our approach is but a modest departure from the SQM formulation. Moreover, the higher dimensionality of our Hilbert spaces is useful in modelling more sophisticated scenarios, such as multiple, staggered runs of an experiment passing through an apparatus simultaneously. Any apparent redundancy in the QDN formalism is always capable of physical interpretation.

We include the preparation switch for the following reason. In SQM, state preparation is regarded as the start of an experiment and state detection is regarded as the end. In our approach, the two processes are regarded as synonymous, in that preparation is itself the outcome of some other process, and detection is but the start of yet another.

In principle we could imagine the physical space between source and detectors as filled with qubits, but these would be redundant here. In the QDN approach, we invoke only that number of qubits sufficient to model the essential physics of a given experiment.

Throughout this paper, we shall suppress the tensor product symbol \otimes , it being implied. Having introduced a rank-three quantum register $\mathcal{R}^3 \equiv \mathcal{Q}_0 \mathcal{Q}_1 \mathcal{Q}_2$ to model the SG experiment, we now discuss a typical run of this experiment. This involves a time-dependent description of the labstate $|\Psi\rangle$. We shall denote all labstate vectors using this modification of the Dirac bra-ket notation, with round angular brackets replacing the traditional angular brackets, reserving the latter to refer to vectors in the SQM formalism. Operators acting over labstates will be denoted in blackboard bold font, such as \mathbb{U} . In the following, all references to time are to laboratory clock time as registered by the observer in the laboratory.

First, imagine the situation after all apparatus has been constructed but

before the actual experiment has started, or between runs. During such a time, the equipment is lying idle, i.e., unused. It exists, but no electron is being prepared and no detector is registering any result. Such a state of the apparatus-laboratory system will be called the *void* state (we shall not use the term *vacuum* in this context, as this is generally used to represent empty space devoid of any matter). We shall represent the void state by the quantum register vector $|\Psi_0\rangle = |0\rangle_0|0\rangle_1|0\rangle_2 = |000\rangle = |0.2^0 + 0.2^1 + 0.2^2\rangle = |0\rangle$.

Suppose now that at some initial time t_{in} , a run of the experiment starts by the process of throwing the preparation switch. At this point the experimentalists will be confident that the source has prepared an initial state and that nothing will have been registered yet by either outcome detector. We represent the labstate at this time by the quantum register state $|\Psi_{in}\rangle = |1\rangle_0|0\rangle_1|0\rangle_2 = |100\rangle = |1.2^0 + 0.2^1 + 0.2^2\rangle = |1\rangle = \mathbb{A}_0^+|0\rangle$, where in this particular case $\mathbb{A}_0^+ \equiv A_0^+ I_1 I_2$. Here, the operator $A_0^+ = |1\rangle_0\langle 0|$ changes the state of preparation switch from the answer *no* to the answer *yes*, whilst I_1 and I_2 are the identity operators acting over \mathcal{Q}_1 and \mathcal{Q}_2 respectively.

We can be sure that there must be such an interval of time, because detectors are generally distinct from sources and therefore can trigger only at non-zero times *after* state preparation, according to one of the fundamental principles of special relativity, a principle which we do not disagree with. All signals registered in our qubits have to be consistent with the causality properties of relativity.

Towards the end of a given run of the experiment, at a time $t_{out} > t_{in}$, the observer may write down the labstate immediately prior to detection, which is given by

$$|\Psi_{out}\rangle = \alpha|010\rangle + \beta|001\rangle = \alpha|2\rangle + \beta|4\rangle = (\alpha\mathbb{A}_1^+ + \beta\mathbb{A}_2^+)|0\rangle, \quad (2)$$

where $\mathbb{A}_1^+ \equiv I_0 A_1^+ I_2$ and $\mathbb{A}_2^+ \equiv I_0 I_1 A_2^+$.

It is important to understand the origin of the coefficients α and β in (2). In SQM, they are calculated from a knowledge of the Hamiltonian and other details involved in the experiment. We observe that a Hamiltonian is not an absolute property of a system under observation, even though it is customary to talk about the "Hamiltonian of a system". It changes according to the context of the experiment. For instance, changing the magnetic field in the SG experiment changes the Hamiltonian. Therefore, even in SQM, what is usually referred to as the Hamiltonian of the system is in practical terms determined by the apparatus. It is only by virtue of classical knowledge previously acquired by an observer about their apparatus that permits a discussion in terms of a Hamiltonian for a system.

Given a Hamiltonian as a depository of acquired knowledge about an experiment, SQM then processes this knowledge via standard rules. In QDN, this knowledge will be represented and processed in a different though equivalent format, one designed to emphasize the apparatus rather than the system. In both SQM and QDN, the ambition is essentially the same however, i.e., to write down coefficients which carry information about the outcome probabilities of an experiment.

A practical difficulty with QDN emerges here. Currently, our experience of QDN is relatively limited. We are working our way towards a comprehensive dynamical theory, which we envisage will give us consistent methods of dynamical calculations entirely within a QDN framework. At this time, however, we have not yet developed the formalism sufficiently to allow us a method of calculating the coefficients α and β without resorting at least somewhere to a knowledge of SQM. It would not be correct to criticize the QDN approach on that account, as the importance of the conceptual issues transcends the significance of the practical difficulties we face at this time.

Given $|\Psi_{out}\rangle$, the Born probability rule adapted to the quantum register can be applied to give the outcome probabilities

$$P(\text{up}|\Psi_{in}) \equiv |(2|\Psi_{out})|^2 = |\alpha|^2, \quad (3)$$

$$P(\text{down}|\Psi_{in}) \equiv |(4|\Psi_{out})|^2 = |\beta|^2,$$

$$P(\text{any other state}|\Psi_{in}) \equiv |(a|\Psi_{out})|^2 = 0, \quad a = 0, 1, 3, 5, 6, 7, \quad (4)$$

consistent with known physics. Of course, during any single run involving a single electron, only one detector gets triggered, so these probabilities have to be related to the frequencies of outcome built up over many runs of the basic experiment.

Normally, after each run is over and before the next one starts, the labstate reverts to the void state $|0\rangle$. The specific mechanism for this is currently beyond known physics, as is the transition from the void state to the initial state at the start of a run. These end-point transitions involve extremely complex processes, such as those associated with the observers themselves and the factors involved in their decision making actions. Virtually nothing is known about this side of physics and it is ignored in SCM on that account, but it is remarkable that Feynman recognized this as an issue worthy of comment. In an influential article on the simulation of physics with computers, he wrote [16] “...we have an illusion that we can do any experiment that we want. We all, however, come from the same universe, have evolved with it, and don’t really have any “real” freedom. For we obey certain laws and have come from a certain past.”

We envisage that any experiment currently devised could be embedded as part of a bigger network, in such a way that what are perceived as state preparation and outcome detection processes are simply parts of the greater network in action. In essence, a laboratory experiment is no more or less than a particular local manifestation of the universe running as a vast quantized detector network. Feynman’s concern about why a given experiment was done in the first place would then find an answer somewhere within the principles governing that greater network. This, however, would require a much greater understanding of large scale quantized networks than we have at present.

3 Formal developments

We may consider changes in the labstate during a run of the SG experiment to be described by unitary evolution over the quantum register \mathcal{R}^3 , viz, $|\Psi_{in}\rangle \rightarrow$

$|\Psi_{out}\rangle \equiv \mathbb{U}(t_{out}, t_{in}) |\Psi_{in}\rangle$, where $\mathbb{U}(t_{out}, t_{in})$ is unitary so as to preserve total probability. Exactly what such an operator is or should be will not always be known, because physics experiments will not in general deal with absolutely every possible state in a quantum register. The basic SG experiment, for example, requires us only to consider four of the eight computational basis elements, viz, $|0\rangle, |1\rangle, |2\rangle$ and $|4\rangle$. It says nothing about the states involving the basis elements $|3\rangle, |5\rangle, |6\rangle$ and $|7\rangle$. Even for such basic experiments as the SG experiment, there is a degree of overkill in the QDN description. This should not be regarded as a flaw however; an analogous situation occurs in all classical and quantum theories. The point is, we only need to know the action of $\mathbb{U}(t_{out}, t_{in})$ on certain states in order to make empirical predictions.

In this context, we can be sure of one or two things with a degree of confidence. We can be confident that in between state preparation and outcome detection, time evolution conserves probability. Also, if the apparatus is in a void state, then we do not expect that to change, unless we initiate a new run (which will not conserve probability anyway). Therefore, we may assume $\mathbb{U}(t_{out}, t_{in}) |0\rangle = |0\rangle$. Then for the SG experiment, for example, we can represent the dynamics in terms of how the transition operators change, viz,

$$\mathbb{A}_0^+ \rightarrow \mathbb{U}(t_{out}, t_{in}) \mathbb{A}_0^+ \mathbb{U}^+(t_{out}, t_{in}) = \alpha \mathbb{A}_1^+ + \beta \mathbb{A}_2^+. \quad (5)$$

More generally, we shall “modularize” our spatio-temporal description, meaning that we shall discuss how individual transition operators change at various times in their own ways. Often we shall leave out specific reference to the \mathbb{U} operators, writing for example $\mathbb{A}_0^+ \rightarrow \alpha \mathbb{A}_1^+ + \beta \mathbb{A}_2^+$ to describe a particular change in the operator \mathbb{A}_0^+ at a particular place and time during a given run.

Because real physics experiments are irreversible, we need to be cautious about what operators such as $\mathbb{U}(t_{out}, t_{in})$ really mean. They will have the semi-group property $\mathbb{U}(t_2, t_1) \mathbb{U}(t_1, t_0) = \mathbb{U}(t_2, t_0)$, $t_2 \geq t_1 \geq t_0$ and satisfy the rule $\mathbb{U}(t_1, t_0) \mathbb{U}^+(t_1, t_0) = \mathbb{I}_{\mathcal{R}}$, where $\mathbb{I}_{\mathcal{R}}$ is the register identity operator, but we need have no clear physical interpretation of what the operator $\mathbb{U}(t_0, t_1)$ means, for $t_0 < t_1$. Time reversal in QDN is regarded as meaningful only as a comparison between different but related networks operating forwards in time, and not in terms of any metaphysical running of a network backwards in time. The apparent time reversal properties of SQM arise only when fundamental issues to do with apparatus are ignored.

4 von Neumann tests

The SG experiment is the most elementary and useful example of the sort of quantum experiment discussed by von Neumann [17], where an ensemble of identically prepared initial states is passed one at a time through some test apparatus A and a range of possible outcomes detected. The description of an idealized version of such an experiment leads to the so-called projection-valued measure (PVM) description of quantum experiments. This is known to have its limitations, but remains an important concept.

The general PVM scenario goes as follows. For each run of an ensemble of runs, the initial state $|\Psi_{in}\rangle$, which will be assumed to be pure, is prepared by some apparatus Σ_0 at time t_{in} . Subsequently, the prepared state is passed through test apparatus A , and one out of d possible outcomes detected at time t_{out} . In von Neumann's approach, $|\Psi_{in}\rangle$ is assumed to be a normalized element of some d -dimensional Hilbert space \mathcal{H} and the test A is represented by some non-degenerate Hermitian operator \hat{A} acting over \mathcal{H} . Because of non-degeneracy, the eigenstates $|a_1\rangle, |a_2\rangle, \dots, |a_d\rangle$ can be normalized and form an orthonormal basis for \mathcal{H} , known as the preferred basis.

Because of completeness, we may write

$$|\Psi_{in}\rangle \rightarrow |\Psi_{out}\rangle = \hat{U}(t_{out}, t_{in}) |\Psi_{in}\rangle = \sum_{i=1}^d \Psi^i |a_i\rangle, \quad (6)$$

where

$$\Psi^i = \langle a_i | \Psi_{out} \rangle = \langle a_i | \hat{U}(t_{out}, t_{in}) | \Psi_{in} \rangle. \quad (7)$$

The Born probability interpretation then predicts the conditional outcome probabilities to be given by $P(a_i | \Psi_{in}) = |\langle a_i | \Psi_{out} \rangle|^2 = |\Psi^i|^2$.

The QDN description of the PVM scenario follows the pattern outlined for the SG experiment above. We associate one qubit with every part of the apparatus wherever a state could be detected and new information acquired. This means one qubit for the preparation switch and one for each of the d possible outcomes. Therefore, we need a rank- $(1 + d)$ quantum register for such a test.

The QDN dynamics is given by the rule $\mathbb{A}_0^+ \rightarrow \sum_{i=1}^d \Psi^i \mathbb{A}_i^+$, where the Ψ^i are given by the conventional quantum calculation (7), so we find $|\Psi_{in}\rangle \rightarrow |\Psi_{out}\rangle = \sum_{i=1}^d \Psi^i \mathbb{A}_i^+ |0\rangle = \sum_{i=1}^d \Psi^i |2^i\rangle$. The conditional probabilities for the d possible outcomes of the experiment are then given by the quantum register Born rule $P(a_i | \Psi_{in}) \equiv |\langle 2^i | \Psi_{out} \rangle|^2 = |\Psi^i|^2$, in agreement with the PVM formalism.

If all experiments were of this form, there would be little advantage in the QDN description. This comes into its own when more than one von Neumann test are coupled together, either in series, parallel, or a combination of both. This is a situation which occurs frequently in quantum optics experiments and which we have discussed in some detail [3]. Another scenario is slit experiments, which we discuss next.

5 Slit experiments

A slit experiment is one where a particle source channels a beam of particles onto two or more openings in an otherwise opaque barrier. Classically, these openings are associated with mutually exclusive pathways for single particles. On the other side of the barrier is a detecting screen, which registers, at local sites, places where individual particles have landed after passage through the slit-barrier. Examples of such experiments are photon diffraction experiments conventionally called Young's double slit experiment and electron diffraction

experiments of both the analogue (Davisson and Germer) type [18] and modern digitized versions of them.

We shall describe a general version of this scenario in the QDN representation as follows. The source is represented as before by single qubit \mathcal{Q}_0 , the preparation switch. Each slit in the barrier is in principle a place where a particle detector could be placed, and therefore, we introduce a qubit $\mathcal{Q}_{B,a}$ for each slit. Here the subscript B refers to "barrier" and the index a is an integer running from $-\infty$ to $+\infty$. On the detecting screen, there will be a countable number of sites on which the particles can land, and so we introduce a qubit $\mathcal{Q}_{D,j}$ for each such site. Here the subscript D stands for "detector". In real experiments involving say photographic film, there will always be a finite number of sites, not a continuum of sites as represented in SQM. In principle, because we could make the detecting screen as large as we want, we shall allow the index j on the detecting qubits to run from $-\infty$ to $+\infty$, as for the slit qubits.

A typical run of the experiment starts, as before, with the apparatus in the void state $|0\rangle \equiv |0\rangle_0 \Pi_{i=-\infty}^{\infty} |0\rangle_{B,i} \Pi_{j=-\infty}^{\infty} |0\rangle_{D,j}$. Then at time $t = 0$, a switch is pulled and a particle is emitted from the source. The labstate is now given by $|\Psi_{in}\rangle = \mathbb{A}_0^+ |0\rangle$.

In the conventional scenario, it is imagined that a Schrödinger wave impinges on the barrier and is split into as many parts as there are slits in it. Each part of the wave then passes through a single slit in the barrier and interference with the other parts takes places on the other side of the barrier to the source. In the QDN representation, the splitting of the wave by the slits in the barrier is represented by the unitary evolution process $\mathbb{A}_0^+ \rightarrow \mathbb{U}_0 \mathbb{A}_0^+ \mathbb{U}_0^+ \equiv \sum_{a=-\infty}^{\infty} \Psi^a \mathbb{A}_{B,a}^+$, where the coefficients Ψ_a depend on the details of the experimental arrangement, but must satisfy the rule

$$\sum_{a=-\infty}^{\infty} |\Psi^a|^2 = 1 \quad (8)$$

in order to conserve probability. This part of the experiment will be referred to as splitting.

The evolution subsequent to splitting, between the barrier and the detector, is where quantum interference takes place. This means, in concrete terms, that the separate beams do not interact classically with each other, apart from superposing, thereby creating a final, superposed wave. In the QDN representation, this part of the experiment is described using two rules. First, each slit behaves as if it were now a preparation switch, i.e., a source of a new PVM experiment, with a collection of detectors at the detector screen. Hence we write $\mathbb{A}_{B,a}^+ \rightarrow \mathbb{U}_1 \mathbb{A}_{B,a}^+ \mathbb{U}_1^+ \equiv \sum_{j=-\infty}^{\infty} U_{aj}^{(1)} \mathbb{A}_{D,j}^+$, where again, unitarity requires us to impose the conditions

$$\sum_{j=-\infty}^{\infty} U_{aj}^{(1)*} U_{bj}^{(1)} = \delta_{ab}. \quad (9)$$

To prove this, we note that the "slit" states $\mathbb{A}_{B,a}^+ |0\rangle$ are mutually orthogonal states in the QDN register, and we simply apply unitary evolution within the left hand side of the inner product $\langle 0 | \mathbb{A}_{B,a} \mathbb{A}_{B,b}^+ | 0 \rangle = \delta_{ab}$.

The second rule involves superposition. Just prior to detection at the detector screen, the labstate is given by

$$|\Psi_{out}\rangle \equiv \mathbb{U}_1 \mathbb{U}_0 \mathbb{A}_0^+ \mathbb{U}_0^+ \mathbb{U}_1^+ |0\rangle = \sum_{a=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \Psi^a U_{aj}^{(1)} \mathbb{A}_{D,j}^+ |0\rangle, \quad (10)$$

from which we read off the transition amplitude A_j of a particle landing on detector j to be given by $A_j = \sum_{a=-\infty}^{\infty} \Psi^a U_{aj}^{(1)}$. Hence the probability P_j that the detector associated with qubit $\mathcal{Q}_{D,j}$ fires, conditional on the experiment as set up, is given by $P_j = |A_j|^2$. It is easy to verify, using the summation rules (8) and (9) that these probabilities sum to unity.

In principle, there is no need to visualize the barrier or detecting screens in terms of standard geometrical objects, such as planes. The barrier and detector sites could be arranged in any sort of spatial configuration whatsoever. It is the coefficients $\{\Psi^a\}$ and the $\{U_{aj}^{(1)}\}$ which determine whether any geometrical interpretation is meaningful. These coefficients are, in line with the interpretation we advocate throughout this paper, manifestations of the physics of the apparatus, not of any imagined system passing through the apparatus.

However, there will be situations where classical information about the distribution of sites within the apparatus permits the use of symmetry arguments. For example, suppose the experiment does indeed involve screens, with the slits equally spaced along a given direction in the barrier plane, and with the detector sites equally spaced along the same direction in the detector plane. If the slits are of equal width and the detectors identical in construction, then spatial homogeneity may allow us to write $U_{aj}^{(1)} \equiv V_{a-j}$, where the complex coefficients $\{V_k\}$ satisfy the rule $\sum_{k=-\infty}^{\infty} V_k^* V_{k+d} = \delta_{0,d}$.

A double slit experiment is a particular version of the above setup such that all but two of the slits are blocked, with the unblocked slits placed in a symmetrical way relative to the source. Suppose the slits labelled by positive integer s and its counterpart $-s$ are unblocked. Then up to the point of splitting, QDN evolution is given by $\mathbb{A}_0^+ \rightarrow \Psi^s \mathbb{A}_{B,s}^+ + \Psi^{-s} \mathbb{A}_{B,-s}^+$, where in the symmetrical case, $|\Psi^s|^2 = |\Psi^{-s}|^2 = 1/2$. Subsequently and just prior to detection, evolution gives

$$\mathbb{A}_0^+ \rightarrow \sum_{j=-\infty}^{\infty} \{\Psi^s V_{s-j} + \Psi^{-s} V_{-s-j}\} \mathbb{A}_{D,j}, \quad (11)$$

so that

$$\begin{aligned} P_j = & |\Psi^s|^2 |V_{s-j}|^2 + |\Psi^{-s}|^2 |V_{-s-j}|^2 \\ & + \Psi^{-s} \Psi^{s*} V_{-s-j} V_{s-j}^* + \Psi^{-s*} \Psi^s V_{-s-j}^* V_{s-j}. \end{aligned} \quad (12)$$

These probabilities sum to unity as required. We see here the appearance of interference terms regardless of the details of the dynamics.

6 Path integrals

In SQM, the Feynman path integral approach [19] utilizes the full power of quantum counterfactuality to rewrite the amplitude for a given initial state of a system to evolve to some final state in terms of all possible paths between the two states. We show in this section how the QDN approach can be recast in path integral terms. Feynman's concept of all possible paths contributing to the amplitude is essentially identical to that of a quantized detector network, with the important difference that the emphasis in Feynman's approach is on states of the system and not on those of the apparatus.

Up to now, the QDN approach has been to suppose that detector qubits are fixed throughout an experiment. This need not be the case in reality. We could imagine an experiment lasting over such a duration that whilst it was still in progress, parts of the apparatus were being constructed or removed. If we went so far as to imagine that the universe itself is some sort of vast quantum process, then this phenomenon of time-dependent apparatus emerges logically. It leads inevitably to the concept of a quantum cosmology where the universe is regarded as a self-interacting, autonomous quantum dynamical system with no external observers. An example of what we mean comes from astrophysics. Astronomers occasionally receive light from a supernova, which shows in the most graphical terms that the source of the light no longer exists in the same form, that of an unexploded star, that it had just prior to the emission of that light.

We do not have the space to discuss this side of the QDN formalism further here, save to make three comments. First, the construction of a consistent, mathematically well-defined quantum cosmology was one of the factors which motivated our ideas [6]. Second, the concept of apparatus changing dynamically is relevant to what happens normally in the world about us. Because of the extreme complexity involved in such changes, however, physicists generally go to great lengths to construct their experiments so as to eliminate as much as possible the effects of apparatus change during the course of their experiments. The result is that in SQM, apparatus is assumed to be fixed, but we emphasize that this is no more than a useful assumption. The QDN approach allows us to go beyond this scenario. Third, we believe that the quantization of general relativity should be tackled through a time-dependent QDN approach or its equivalent, because space, time and metric are inherently aspects of the process of observation and not intrinsic properties of systems under observation.

We shall calculate the amplitude for a QDN to go from an initial labstate at time 0 to some final labstate at time N , where N is some positive integer. In our approach, time is necessarily discrete, because the process of information extraction is never instantaneous (the change from the concept of continuous time to discrete time is a logical one once we move away from systems and discuss matters in observational terms). Therefore, the labstate associated with the apparatus will be assumed to evolve in a finite sequence of steps, called stages, each labelled by an integer n running from zero to N . The physical time between successive stages need not be uniform, however, or small, such

as on Planck scales. We note in passing that the Feynman path integral is usually formulated via a discretization of time, and that the continuum limit is generally ill-defined, if not formally non-existent. We have no such problem in the QDN approach, because the continuous time limit is not one that we believe is strictly in accordance with the observational facts of quantum experiments. We believe that the continuous time concept is meaningful only in so far as there are virtually limitless degrees of freedom associated with the observer. In the scenario mentioned above, concerning Feynman's statement about the freedom of choice in an experiment, we imagine any experiment being part of a greater network described by vastly many qubits, and then a description of that greater network might well be more efficient in terms of continuous variables. There is an analogy here with the relationship of classical thermodynamics to statistical mechanics.

Taking into account the idea that the qubits associated with the apparatus at time n may be different to those at time $n + 1$, we shall label the operators and labstate associated with time n with the index n . We shall suppose that there are r_n qubits involved at time n .

At time zero, after the preparation switch has been thrown for qubit \mathcal{Q}_{0,i_0} , $1 \leq i_0 \leq r_0$, the labstate is given by $|\Psi_0, i_0\rangle \equiv \mathbb{A}_{0,i_0}^+ |0\rangle$, where $1 \leq i_0 \leq r_0$. At the next stage, the labstate is given by the transition rule $|\Psi_0, i_0\rangle \rightarrow \mathbb{U}_1 |\Psi_0, i_0\rangle = \sum_{i_1=1}^{r_1} U_{i_0 i_1}^{(1)} \mathbb{A}_{1,i_1}^+ |0\rangle$, where the complex coefficients $\{U_{i_0 i_1}^{(1)}\}$ satisfy the "unitarity" rule

$$\sum_{i_1=0}^{r_1} U_{i_0 i_1}^{(1)} U_{j_0 i_1}^{(1)*} = \delta_{i_0 j_0}, \quad 1 \leq i_0, j_0 \leq r_0. \quad (13)$$

There is no reason to expect r_1 to be necessarily equal to r_0 , so the matrix $U_{ij}^{(1)}$ is not necessarily square, and therefore, not necessarily a unitary matrix in the conventional sense.

At time $t = 1$, if no measurement is taken, each of the qubits involved with the labstate at that time becomes a preparation switch for the next step of the evolution. Therefore, we simply iterate the process in the same way, giving

$$|\Psi_0, i_0\rangle \rightarrow \mathbb{U}_2 \mathbb{U}_1 |\Psi_0, i_0\rangle = \sum_{i_1=1}^{r_1} \sum_{i_2=1}^{r_2} U_{i_0 i_1}^{(1)} U_{i_1 i_2}^{(2)} \mathbb{A}_{2,i_2}^+ |0\rangle, \quad (14)$$

where the coefficients $\{U_{i_1 i_2}^{(2)}\}$ satisfy a corresponding unitarity rule.

Taking this process all the way to time N gives us

$$|\Psi_0, i_0\rangle \rightarrow \mathbb{U}_N \mathbb{U}_{N-1} \dots \mathbb{U}_1 |\Psi_0, i_0\rangle = \sum_{i_N=1}^{r_N} \dots \sum_{i_2=1}^{r_2} U_{i_0 i_1}^{(1)} \dots U_{i_{N-1} i_N}^{(N)} \mathbb{A}_{N,i_N}^+ |0\rangle. \quad (15)$$

From this, we read off the amplitude $\mathcal{A}(i_0, i_N)$ for the labstate to go from

$\mathbb{A}_{0,i_0}|0\rangle$ to $\mathbb{A}_{N,i_N}|0\rangle$ to be given by

$$\mathcal{A}(i_0, i_N) = \sum_{i_{N-1}=1}^{r_{N-1}} \dots \sum_{i_1=1}^{r_2} U_{i_0 i_1}^{(1)} \dots U_{i_{N-1} i_N}^{(N)}. \quad (16)$$

This is our path integral formulation of QDN dynamics.

The above formulation is not the most general conceivable. It is based on the detector network changing in a predetermined, classical manner independent of the labstate. A more subtle concept would be to link the changes in the network qubits with changes in the labstate [20]. This gives an altogether more dynamical view of the universe. It is our belief that something like this is the proper way to discuss quantum gravitation.

7 The POVM formalism

The PVM formulation of quantum physics eventually became superseded by the more general POVM (positive operator-valued measure) approach [21]. In this latter approach, quantum experiments can have more or less outcomes than the dimension of the Hilbert space involved in the description of the prepared state. For example, suppose we have an experiment with k possible outcomes, with k not necessarily equal to d , the dimension of the Hilbert space \mathcal{H} used to model the states of the system. For each outcome $|\phi^i\rangle$, $i = 1, 2, \dots, k$, there is an associated positive operator \hat{E}_i , such that

$$\sum_{i=1}^k \hat{E}_i = \hat{I}_{\mathcal{H}}, \quad (17)$$

where $\hat{I}_{\mathcal{H}}$ is the identity operator over the Hilbert space. Given a normalized initial state $|\Psi\rangle \in \mathcal{H}$, then the conditional probability $P(\phi^i|\Psi)$ of outcome $|\phi^i\rangle$ is given by $P(\phi^i|\Psi) = \langle\Psi|\hat{E}_i|\Psi\rangle$, with condition (17) ensuring probabilities sum to unity.

The above discussion involves pure states. The POVM approach is not restricted to these and can be extended to cover mixed states, which requires a density matrix approach involving the taking of traces. We shall not discuss mixed states in this paper, as the generalization of QDN to cover such cases is not anticipated to be particularly difficult and is left as an exercise for the reader.

The disadvantage of the POVM approach is that it masks the spatio-temporal structure of the measurements involved and suggests that the simple in-out architecture of a single von Neumann test is all that is going on. In reality, complex experiments involve sequences of processes rather like computations in a computer, which is why quantum computation is one possible way to approach physics [16].

The QDN approach readily deals with situations discussed by the POVM formalism in SQM. We have shown [3] how readily a quantum optics experiment

discussed recently by Brandt using a POVM description [21] can be discussed using QDN, with the advantage that it is conceptually more understandable than the POVM approach. In particular, all of the detector qubits are treated in the same way, whereas the status of the detectors in the POVM approach is considered inequivalent. This is because two of the three detectors involved project onto non-orthogonal states in the SQM Hilbert space involved. The QDN description of the experiment makes it clear that the original formulation of the experiment in terms of non-orthogonal basis vectors is not necessary, and is induced by the choice of apparatus.

8 Higher rank states

A feature of the formalism developed thus far is that, apart from the void state, all physical states discussed have been of the form $|2^k\rangle \equiv \mathbb{A}_k^+|0\rangle$ or linear combinations of them. Such states will be called *rank-one states*. We generalize the concept of state rank as follows.

Given a rank- r quantum register $\mathcal{R}^r \equiv \mathcal{Q}_0\mathcal{Q}_1\mathcal{Q}_2\ldots\mathcal{Q}_{r-1}$ and its associated computational basis $B^r \equiv \{|a\rangle : 0 \leq a < 2^r\}$, we define the *rank- p subsets* B_p^r of B^r as follows: $B_0^r \equiv \{|0\rangle\}$, $B_1^r \equiv \{\mathbb{A}_a^+|0\rangle : 0 \leq a < 2^r\}$, $B_2^r \equiv \{\mathbb{A}_a^+\mathbb{A}_b^+|0\rangle : 0 \leq a < b < 2^r\}$, \ldots , $B_r^r \equiv \{\mathbb{A}_0^+\mathbb{A}_1^+\ldots\mathbb{A}_{r-1}^+|0\rangle\}$. There are $r+1$ such subsets.

The cardinality $\#B_p^r$ of B_p^r is given by $\#B_p^r = \frac{r!}{(r-p)!p!}$. The rank- p subsets are disjoint and exhaustive, i.e., $B_p^r \cap B_q^r = \emptyset$ for $p \neq q$, and $B_0^r \cup B_1^r \cup \ldots \cup B_r^r = B^r$. The elements of B_p^r are linearly independent vectors in \mathcal{R}^r and therefore form an orthonormal basis for a vector subspace of dimension $\#B_p^r$, which we shall denote by \mathcal{R}_p^r . Any vector in \mathcal{R}_p^r will be called a rank- p state. Each rank- p subspace \mathcal{R}_p^r is a bona-fide Hilbert space, but apart from the trivial subspaces \mathcal{R}_0^r and \mathcal{R}_r^r , is *not* a quantum register.

Different level subspaces have only the zero vector $\mathbf{0}_{\mathcal{R}}$ of \mathcal{R}^r in common, i.e., $\mathcal{R}_p^r \cap \mathcal{R}_q^r = \{\mathbf{0}_{\mathcal{R}}\}$, $p \neq q$, and so we deduce $\mathcal{R}_0^r \oplus \mathcal{R}_1^r \oplus \ldots \oplus \mathcal{R}_r^r = \mathcal{R}^r$, where \oplus denotes the direct sum of the subspaces concerned.

9 Interpretation of higher rank labstates

There are important situations in QDN physics where labstates of rank higher than one are encountered naturally. We discuss some of these next.

9.1 Independent experiments

Suppose two SG experiments, A and B , are performed separately and completely independently of each other in different parts of the universe. In such a case, we can describe the two experiments by a single rank-6 QDN involving rank-2 states as follows. First, we assign qubits $\mathcal{Q}_0, \mathcal{Q}_1, \mathcal{Q}_2$ to experiment A and qubits $\mathcal{Q}_3, \mathcal{Q}_4$ and \mathcal{Q}_5 to experiment B . Now suppose experimentalists at each of the two laboratories have agreed to run separate runs of their experiments

simultaneously. Then the initial labstate of the simultaneous experiments over the rank-6 network is given by

$$|\Psi_{in}\rangle = \mathbb{A}_0^+ \mathbb{A}_3^+ |0\rangle = |2^0 + 2^3\rangle = |9\rangle. \quad (18)$$

If now each experiment is truly independent, then the dynamics followed by the qubits associated with each experiment are independent, and so we can write $\mathbb{A}_0^+ \rightarrow \alpha \mathbb{A}_1^+ + \beta \mathbb{A}_2^+$ and $\mathbb{A}_3^+ \rightarrow \gamma \mathbb{A}_4^+ + \delta \mathbb{A}_5^+$, where $|\alpha|^2 + |\beta|^2 = |\gamma|^2 + |\delta|^2 = 1$. Hence

$$|\Psi_{in}\rangle \rightarrow |\Psi_{out}\rangle = (\alpha \mathbb{A}_1^+ + \beta \mathbb{A}_2^+) (\gamma \mathbb{A}_4^+ + \delta \mathbb{A}_5^+) |0\rangle = |\psi\rangle_A \otimes |\phi\rangle_B, \quad (19)$$

where $|\psi\rangle_A \equiv \alpha |0\rangle_0 |1\rangle_1 |0\rangle_2 + \beta |0\rangle_0 |0\rangle_1 |1\rangle_2$ and $|\phi\rangle_B \equiv \gamma |0\rangle_3 |1\rangle_4 |0\rangle_5 + \delta |0\rangle_3 |0\rangle_4 |1\rangle_5$. In other words, independent experiments are modelled in QDN by separable states of rank higher than unity over a single (universal) network.

In such scenarios, sets of coefficients such as $\{\alpha, \beta\}$ and $\{\gamma, \delta\}$ associated with separate experiments will be functionally independent if the associated experiments are truly independent. This means in practical terms that if the experimentalists associated with A were to change the orientation of the main magnetic field in their apparatus, thereby changing α and β , there would be no change in $|\phi\rangle_B$. The same would hold for B . If the experiments were too close, however, we might imagine that the magnetic field of one would overlap that of the other, so that changes in one field would be detected in the other apparatus. The two sets of coefficients would then no longer be independent.

The possibility of discussing independent quantum processes within a universal QDN by a separable labstate is complemented by the possibility of having entangled labstates. For example, we could construct an experiment where the output channels of A and B in the above were separable but were subsequently fed into a third apparatus C which had only entangled outcomes. Particle scattering experiments are of this type.

9.2 Change of rank experiments: (EPR)

Experiments of the type discussed by Einstein, Podolsky and Rosen [4] cause conceptual problems because they confront the classical system concept with quantum non-locality. The QDN approach avoids this problem by simply not referring to the system concept at all.

Suppose we prepared a spin-zero bound state of an electron and a positron, given in SQM by $|\Psi\rangle = 2^{-1/2} \left\{ |+\mathbf{k}\rangle_e |-\mathbf{k}\rangle_p - |-\mathbf{k}\rangle_e |+\mathbf{k}\rangle_p \right\}$, where the subscripts e and p refer to electron and positron respectively. Alice and Bob are two well-separated observers, each with their own particle species filters and SG equipment. Alice can detect and test for electron spin only, whereas Bob can detect and test for positron spin only. Alice sets her quantization axis along $\mathbf{k} = (0, 0, 1)$, whereas Bob sets his along direction $\mathbf{a} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$. It is known that whenever Alice finds that an electron has passed through her apparatus with spin $|+\mathbf{k}\rangle$, Bob will have found his positron had passed through

his apparatus via either of the $|+\mathbf{a}\rangle$ or $|-\mathbf{a}\rangle$ channels in a random way, with frequency given correctly by quantum mechanics.

The QDN description requires a minimum of five qubits; one for the preparation switch, two for Alice's SG apparatus outcomes and two for those of Bob's apparatus. To determine the QDN dynamical rules, we look at the SQM calculation. We recall that the standard rules permit us to rewrite the prepared state in the form

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left\{ \begin{array}{l} \sin(\frac{1}{2}\theta)e^{-i\phi}|+\mathbf{k}\rangle_e|+\mathbf{a}\rangle_p + \cos(\frac{1}{2}\theta)e^{-i\phi}|+\mathbf{k}\rangle_e|-\mathbf{a}\rangle_p \\ -\cos(\frac{1}{2}\theta)|-\mathbf{k}\rangle_e|+\mathbf{a}\rangle_p + \sin(\frac{1}{2}\theta)|-\mathbf{k}\rangle_e|-\mathbf{a}\rangle_p \end{array} \right\}. \quad (20)$$

This is the form which relates best to the experiment as actually done. We use this form to determine the transition rules for the labstate. We require the QDN dynamics to satisfy the rule

$$\mathbb{A}_0^+ \rightarrow \frac{\sin(\frac{1}{2}\theta)}{\sqrt{2}}(e^{-i\phi}\mathbb{A}_1^+\mathbb{A}_3^+ + \mathbb{A}_2^+\mathbb{A}_4^+) + \frac{\cos(\frac{1}{2}\theta)}{\sqrt{2}}(e^{-i\phi}\mathbb{A}_1^+\mathbb{A}_4^+ - \mathbb{A}_2^+\mathbb{A}_3^+), \quad (21)$$

which then leads to the same predicted probabilities as for the SQM calculation.

We see here an example of a rank-one state evolving into a rank-two state. The initial labstate is of rank one at the point of preparation, because that is the physics of the preparation process. It is only because the detection equipment is arranged so as to trigger in two separate places that the final state is legitimately a rank-two state. Without any reference to the detecting equipment, it is meaningless to talk about the prepared state being an entangled state of an electron and a positron. Entanglement is not a fundamental property of a system, but determined by how we observe it. This is entirely consistent with Bohr's view of the EPR experiment.

9.3 Two-particle interferometry

In 1989, Horne, Shimony and Zeilinger discussed an experiment where an entangled two-photon state passes through a device consisting of beamsplitters, mirrors, and phase-shifters [23]. The quantities of interest are the two-particle coincidence count rates and their dependence on the variable phase-shift angles, which can be varied at will throughout the experiment. The conventional representation of the initial state is

$$|\Psi_{in}\rangle = \frac{1}{\sqrt{2}} \{ |\mathbf{k}_A\rangle_1 |\mathbf{k}_C\rangle_2 + |\mathbf{k}_D\rangle_1 |\mathbf{k}_B\rangle_2 \}, \quad (22)$$

where the wave vectors \mathbf{k}_A , \mathbf{k}_B , \mathbf{k}_C and \mathbf{k}_D are identified with qubits \mathcal{Q}_1 , \mathcal{Q}_2 , \mathcal{Q}_3 and \mathcal{Q}_4 respectively, and subscripts 1 and 2 refer to the two particles involved.

The QDN account of this experiment[3] gives the dynamical rule

$$\mathbb{A}_0^+ \rightarrow \frac{1}{\sqrt{2}} \{ \mathbb{A}_1^+\mathbb{A}_3^+ + e^{i\theta}\mathbb{A}_2^+\mathbb{A}_4^+ \}, \quad (23)$$

where the angle θ depends on the detailed placement of the various pieces of equipment [23] at the start of the network, which is the point at which the two-photon properties start to manifest themselves. The detailed QDN calculation [3] shows how this entangled rank-two state evolves, in agreement with the calculation of Horne, Shimony and Zeilinger [23] for the two-particle coincidence probabilities.

9.4 Other scenarios involving higher rank labstates

Obvious candidate experiments involving higher rank labstates which remain to be discussed via the QDN approach are *i*) interference of photons from different sources, *ii*) teleportation, *iii*) experiments where a sequence of wave-pulses is set up moving towards target detectors, and *iv*) large scale aggregates of quantum optics modules involving beamsplitters, mirrors and phase-shift devices.

10 Critique and concluding remarks

Many interesting physical ideas remain to be explored in QDN. Apart from the technical challenge of applying the QDN description to ever more complex experimental situations, there remains the question which dominates modern theory, viz, the relationship between quantum mechanics and general relativity. This continuation of the Bohr-Einstein debate arises because of an almost universal belief in the system concept. By avoiding this concept directly, the QDN approach bypasses this debate and all the conceptual problems with it.

However, the picture is not yet complete. It is one thing to write down a QDN expression analogous to a path integral for a scattering amplitude; it is another to understand why the various qubits in the network were involved in the first place. Something is still missing. Until we can understand why a particular network has the structure that it has, we cannot claim that quantum mechanics is a complete description of reality. Although we believe that Bohr won his debate, Einstein was right to doubt the completeness of SQM. Feynman, who disdained philosophy, understood that this point is a legitimate one for physicists to think about and this has motivated us to keep looking into this issue.

Central to this issue is the status of space. We do not believe it is something which exists in its own right. From the QDN point of view, space is a potential for observation and no more than that. That is why in experiments such as the SG experiment, we need focus only on three qubits. If we wanted to go much further and discuss for example black hole physics, we would have to be much more careful in the construction of our quantized detector network. It would involve vastly more qubits. In particular, we would have to understand much more about the dynamical relationship between the evolution of the labstate and the evolution of the network. Such an understanding would give us the quantum version of the classical understanding of the interaction between matter

and spacetime which is encoded in Einstein's equation $G^{\mu\nu} = \kappa T^{\mu\nu}$ in general relativity.

Acknowledgements

I am indebted to Lino Bucchini, Mark Stuckey, Metod Saniga, Jon Eakins, and my students Jason Ridgway-Taylor and Thomas Marlow for many discussions. I am also very grateful to Michel Planat for his invaluable support at a critical time.

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